Presented at EPIC conference
Third European Conference on Energy Performance and Indoor Climate in Buildings
Lyon, France October 23-26, 2002

COMPARING ZONAL AND CFD MODEL PREDICTIONS OF INDOOR AIRFLOWS UNDER MIXED CONVECTION CONDITIONS TO EXPERIMENTAL DATA

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ABSTRACT

The present work is part of a research effort aimed at integrating a detailed model of airflow in large spaces with an algebraic multizone infiltration model to describe pollutant transport and coupled air flows within and between complex buildings and large spaces. In the past 15 years, zonal models were developed with the goal to obtain an approximate prediction of airflow characteristics in large indoor spaces. Also, reducing the number of grids in CFD models is a natural way of decreasing their demand of computational resources to solve air flows in room.

Therefore, we compare the ability of both zonal and coarse-grid k-ε RANS models to predict air flows and temperature profiles in a two-dimensional building zone. Both predictions are compared with conventional k-ε RANS models results and experimental data under mixed convection conditions. Our results suggest that zonal models constitute a suitable tool to assess thermal comfort in a room, and that coarse-grid k-ε RANS is an appropriate method to quickly estimate details of airflows in a room.

KEYWORDS

Indoor air, simulation, zonal, RANS-CFD, ventilation, mixed convection.

INTRODUCTION

Indoor environment design requires detailed information about air distribution, such as airflow pattern, velocity, temperature, humidity, and pollutant concentrations. Because experimental measurement cannot be a practical design tool, various numerical methods have been developed to simulate the indoor environment. A popular approach of computational simulation is Computational Fluid Dynamics (CFD) methods. However, solving commonly used turbulence models requires fast computers with large amount of memory. So this approach has mostly been limited to study details of air distribution in single rooms.

Multizone infiltration and airflow models such as COMIS (Feustel and Rayner-Hooson, 1990) have been developed to predict air flows in complex buildings. These models are suitable tools to design ventilation systems for complex buildings, as well as to provide necessary inputs for energy analysis tools such as EnergyPlus (Crawley et al., 2000). They can predict air flows and contaminant transport within the entire building, but based on a strong assumption. This building is defined as a set of well-mixed volumes or *zones* of homogeneous composition. While this assumption can be acceptable for small rooms or *zones*, it becomes unacceptable when modeling large indoor spaces such as atria and auditoria.

The present work is part of a research effort aimed at integrating a detailed model of airflow in large spaces with an algebraic multizone infiltration model to describe pollutant transport and coupled air flows within and between complex buildings and large spaces. In the past 15 years, a third family of modeling methods, the zonal method, was developed with the goal to obtain an approximate prediction of airflow characteristics in large indoor spaces. Also, reducing the number of grids in CFD models is a natural way of decreasing their demand of computational resources to solve air flows in a room. In this paper, we first present the zonal method and the simulation environment used to solve the corresponding set of equations, and then compare the ability of both zonal and coarse grid CFD modeling approaches to estimate airflows and temperature profiles in a room under mixed convection conditions. Both model predictions are compared with conventional k-ε CFD results and experimental data.

MODELING METHODS

Zonal Method

Model Description

Zonal models are based on an approach that is intermediate between single-air-node models, which give no information about air flow patterns, and CFD models, which give detailed temperature and flow distributions but are computationally intensive. Such intermediate models execute much faster than CFD calculations yet model heat and mass transfer in greater detail than the single-node approach and provide temperature, concentration, and flow distributions that are detailed enough to evaluate thermal comfort and indoor air quality.

Zonal methods are based on solving the pressure field to predict airflow and temperatures in large indoor spaces (Wurtz et al., 1999). In the zonal method, the room is subdivided into a number of control volumes or *cells* in which temperature and density are assumed to be homogeneous, while pressure varies hydrostatically. Mass and thermal energy balances are applied to each cell, with air treated as an ideal gas. The model of airflow between adjacent cells is based on methods used for flows in ducts. In these methods, the mass flow rate $qm_{i,j}$ across the section of area S separating the cells i and j is assumed to be governed by a power-law equation such as: ,

$$qm_{i,j}\, l\, dz = C_d\, \rho\, S\, (\Delta P_{i,j})^{1/2}\, l\, dz \qquad (6)$$

where ρ is air density across the element and C_d a discharge coefficient. The pressure drop $\Delta P_{i,j}$ is expressed as: $\Delta P_{i,j} = (P_i - \rho_i\, g\, z_i) - (P_j - \rho_j\, g\, z_j)$. Also, the thermal energy flow is determined using a convection-diffusion relationship across the surface between two cells.

This standard formulation of zonal models has proven its ability to estimate airflow and temperature distribution in rooms where the flow is weak (Inard et al., 1996; Musy et al., 2001). On the other hand, high velocity regions of the room need to be modeled with specific sets of equations to capture the flow (Wurtz et al., 1999). This approach is illustrated in the next section where a jet model is patched on to the standard zonal model describe the velocity profile within the downstream flow an air intake ventilation slot.

The simulation environment SPARK

SPARK is a simulation environment that supports the definition of simulation models and solution of these models via a robust general differential/algebraic equation solver (Sowell and Haves, 2001). In SPARK, the modeler describes the set of equations defining a model as equation-based objects. At the lower level, an atomic object characterizes one equation and its variables. Then, macroscopic objects can be created as an assembly of various atomic or macroscopic objects. It is not necessary to order the equations, or to express them as assignment statements. Therefore, the modeler can focus only on developing component or element models and let SPARK find the way to solve the implicitly defined problem. This object-oriented approach allows the user to easily test new models and share his library with other modelers.

SPARK uses a specific methodology to handle the numeric process. A graph theory-based algorithm reduces the set of variables to iterate on by identifying strong components within the equation system to be solved. This approach makes the solver very efficient and can significantly minimize simulation time. For these different reasons we have chosen SPARK as simulation environment.

CFD methods

Computational Fluid Dynamics methods have been widely used to predict airflow, temperature or pollutant concentration distributions in rooms. The one most commonly used in this field solve Reynolds Averaged Navier-Stockes (RANS) equations with turbulence modeling using two equations for the transport of turbulent kinetic energy and its dissipation rate. This method is computationally more intensive than the solution of zonal models and requires large amounts of memory. So practically, this method has proven its ability to estimate indoor characteristics mainly in single rooms (Chen, 1996).

Long time period simulations remain difficult in practice. That’s why research developments were done to characterize predictions from CFD models under simplifying assumptions aimed at decreasing the computation time. One effort was to use a Prandtl’s zero-equation turbulence model and another to reduce the size of the simulation domain grid (Chen and Xu, 1998). The first assumption decreases the number of equations to solve while the second reduces the number of elements where RANS equations are discretized. Both decrease the computational effort to the detriment of accuracy.

In a separate research effort we showed that coarse grid k-ε RANS models give a satisfactory estimate of the details of airflows in an isothermal ventilated room. (Mora et al., 2002). In the next section, we’ll present details of airflow and temperature distributions in a ventilated room under mixed convection. Results obtained from both zonal and coarse grid k-ε RANS models are compared with conventional k-ε RANS model predictions and experimental data. All k-ε RANS model predictions have been computed using the commercial software StarCD.

RESULTS AND DISCUSSION

Case study

Zhang et al. (1992) developed an experimental facility to provide measurements of the mean and turbulent behavior of room ventilation flows. An outer room with an HVAC (Heating, Ventilating, and Air-Conditioning) system simulates different weather conditions by controlling the environment around the test room (see figure 1) which is equipped with its own HVAC system, and of a uniform floor heating system of 48 controllable panels to simulate internal heat loads. Velocities and temperature were measured at 205 locations in the central vertical section of the test room with a 1D hot-wire anemometer and a thermocouple, respectively, with an automatic computer-controlled system for data acquisition and probe positioning.

In the test case P6 presented by Zhang et al. (1992), air enters the test room through the diffuser at velocity U_{ref} of 1.71 m.s^{-1} (Re_d = 5800) and a temperature T_d of 23.1°C, while the floor temperature T_f is maintained at 39.7°C (Gr = 3.7E11). Under these mixed convection conditions, measurements indicated that the flow inside the room was two-dimensional except very close to the end walls.

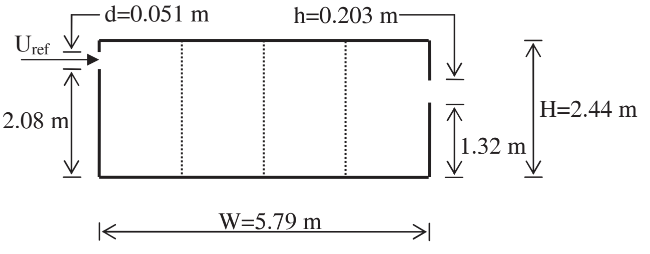

Figure 1: Zhang experimental setup

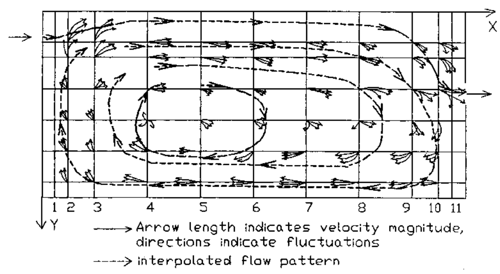

Figure 2: Airflow visualization made by smoke injection (Zhang et al., 1992)

Predictions vs. experimental Data

In this section, we’ll present airflow patterns, velocity and temperature distributions predicted from zonal and k-ε RANS models for Zhang et al.’s configuration presented above. Then, all predictions will be compared with experimental data.

Airflow patterns

Zhang et al. used a smoke injection technique for room airflow pattern visualization within the experimental setup. Their observations are reproduced in Figure 2. A jet is produced downstream the inlet slot, and crosses all the test room, to finally create a flow recirculation over the entire room.

- Zonal model predictions:

Figures 3 and 4 present airflow patterns obtained from zonal models with no jet model and with a semi-empirical jet model from Rajaratnam (1976), respectively. In the first case, when no particular functions are patched onto the standard model to characterize the jet, the former falls down very quickly at the first quarter (*x/W*=0.25) of the test room since the incoming air temperature is about 2.5°C lower than the average inner air temperature. In the second case, momentum is well characterized by adding a jet model into the standard zonal model. In this case the overall recirculation prediction is satisfactory, compared with experimental airflow visualizations.

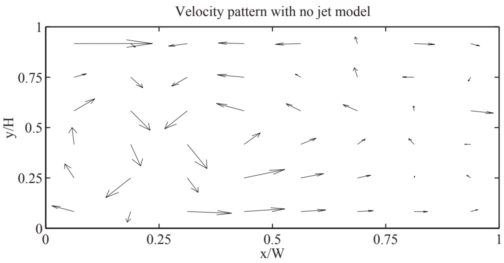

Figure 3: Airflow pattern from standard 8x6 zonal model

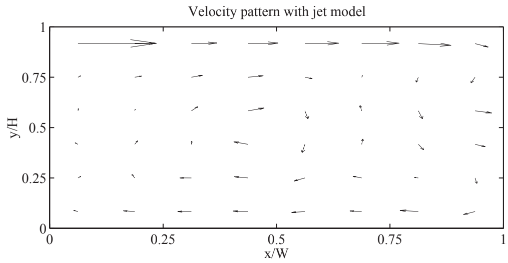

Figure 4: Airflow pattern from 8x6 zonal model with jet model

So in this case, where most of flow driving forces are due to the momentum added to air by the jet, a good estimation of airflow patterns with zonal models requires modeling the jet carefully.

- CFD model predictions:

We performed two-dimensional conventional and coarse-grid k-ε RANS simulations of Zhang test room with domain grids ranging from 8x8 to 73x57 cells. For 10x10 and 15x15 grids the dimension of cells adjacent to the wall was set to 10 cm.

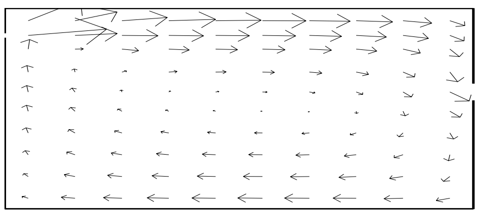
Figure 5: Airflow pattern from 10x10 RANS model

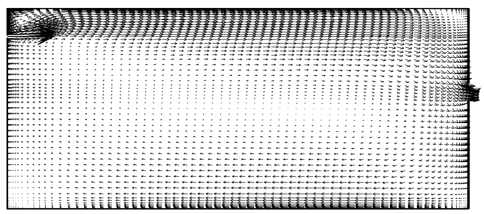
Figure 6: Airflow pattern from 73x57 RANS model

Figures 5 and 6 present airflow patterns obtained from 10x10 and 73x57 k-ε RANS models, respectively. In both cases, the main recirculating flow predictions are in agreement with experimental airflow visualizations. In order to compare quantitatively airflow predictions with experimental data, in the next subsection we present velocity profile comparisons along three vertical lines at *x/W*=0.25, 0.5, and 0.75.

Velocity field

- Zonal model predictions:

In figure 7, we present speed predictions obtained by different zonal models with a jet model. Since velocity measurements were done using a one-dimensional hot-wire probe, we do not have access to horizontal and vertical components of the velocity. All zonal models give a satisfactory speed estimate in the jet region, while the recirculation (speed in the lower section of the room) is underestimated.

- CFD model predictions:

One-dimensional hot-wire probe can only capture the resultant of the velocity, including fluctuations. Since k-ε RANS model predict averaged values of velocity components, we had to add fluctuating terms to predicted values before calculating the module of the velocity to be compared with experimental data. Assuming turbulence isotropy and normal distribution of fluctuating terms, one can sample the distribution (1000 elements in this case) to get a fluctuating terms population. Then, those terms were added to average predictions. Figure 8

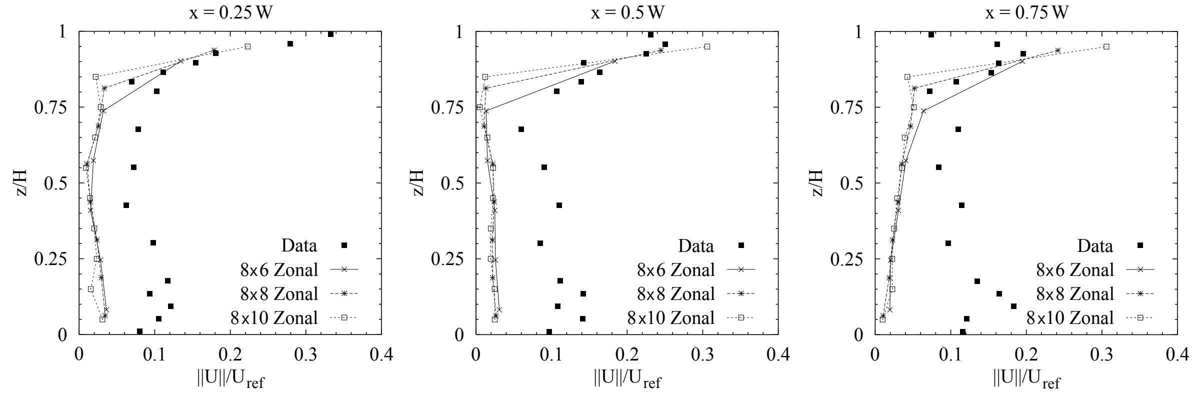

Figure 7: Velocity profiles from zonal models with jet

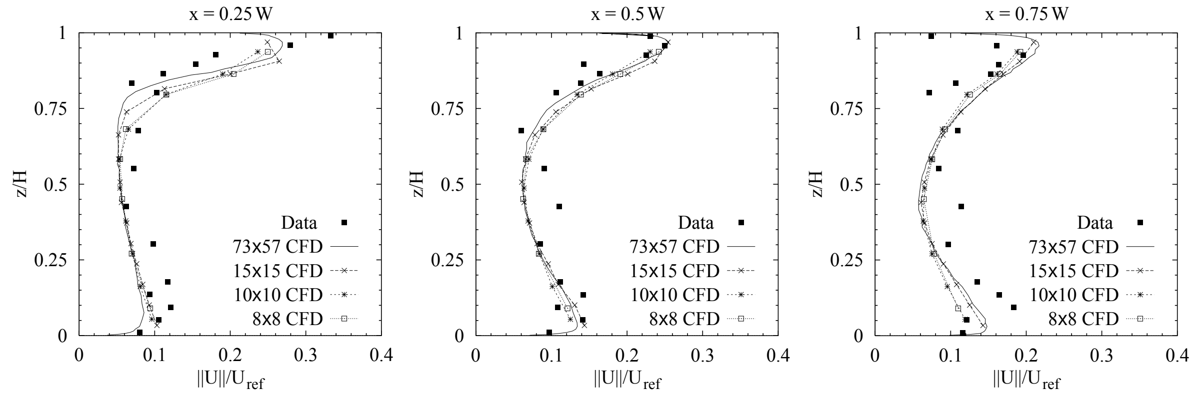

Figure 8: Velocity profiles from k-ε RANS models

presents corrected velocity profiles obtained with k-ε RANS models compared with experimental data.

In all three sections, k-ε RANS models predictions give a satisfactory estimate when compared with experimental data. The jet section is well characterized, and the recirculation slightly underestimated especially in the vertical section located at x=0.75W. In the previous subsection, we saw how dependent was the results of zonal models on user expertise according to the jet modeling. With those k-ε RANS model results, almost no expertise is required. Nevertheless, a subsequent research effort is required to characterize the way to determine coarse grid definition with regard to prediction accuracy.

Temperature field

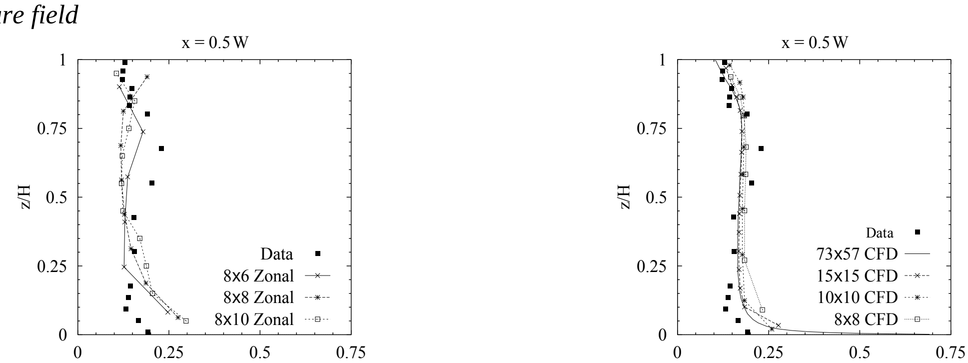

Figure 9: Temperature profiles from zonal models on the left and k-ε RANS models on the right

When comparing temperature profiles along the central vertical line (x=0.5W), all models used give a satisfactory agreement with experimental data. We have presented only one section of the room for brevity since both classes of models present the same behavior in all three sections. We can only see some small discrepancies in the lower region, where we saw that velocities were underestimated. So, when no more details are required, one can choose zonal models as a suitable tool to assess thermal comfort in rooms. On the other hand, when more details of airflows are required (e.g. pollutant transport modeling) one may choose k-ε RANS models.

CONCLUSION

In this paper, we compared the ability of zonal models and, conventional and coarse grid k-ε RANS models to predict airflows and temperature distribution in a two dimensional ventilated room under mixed convection conditions. In this configuration, zonal models give a satisfactory estimate of airflow patterns only with specific laws to model momentum added to air by the jet. Zonal models give a rough estimate of the structure of the recirculation in the room, whereas all k-ε RANS velocity predictions are in good agreement with experimental data. Finally, both classes of models are able to assess temperature profiles in the room. So zonal models can be a suitable tool to estimate thermal comfort in a ventilated room, when details of airflow are required coarse grid k-ε RANS models can give quicker velocity profiles estimates than conventional k-ε RANS models. More research effort should be done to determine a tradeoff between grid coarseness and results accuracy.

AKNOWLEDGMENT

This research was supported by the Office of Non-proliferation and National Security, Chemical and Biological Non-proliferation Program of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. We would like to thank particularly E. FINLAYSON for her generous advice about using the software StarCD, and D. CURTIL for his technical help with using SPARK. This work is also part of a Ph.D. thesis financed by the French Agency for Environment and Energy Management (ADEME).

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